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Integrating Citizen-generated Data from Citizen Science with the Sustainable Development Goals

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Integrating Citizen Science and Community-based Monitoring with the United Nations Sustainable Development Goals

Abstract: The UN Sustainable Development Goals (SDGs) are largely reliant on traditional data sources for reporting, yet they could benefit from greater exploitation of non-traditional data, particularly citizen science and community-based monitoring. Here we provide examples of how citizen science and community-based monitoring are already contributing to the SDG indicators and the potential for where they might fill existing gaps. To achieve better integration of citizen science and community-based monitoring with the SDGs requires a number of actions, which are laid out in a roadmap for moving forward.

Advances in technology and the proliferation of big data are providing new opportunities for monitoring and tracking the progress of the United Nations (UN) Sustainable Development Goals (SDGs)[1]. As the latest framework for assessing and monitoring the alleviation of poverty, inequalities and environmental degradation, progress on meeting the 17 SDGs is evaluated through reporting on a hierarchy of 169 targets and 232 indicators[2]. Here we argue that citizen-generated data can complement and ultimately transform the SDG reporting process; these are the data produced by citizens and their organizations in monitoring issues that affect them in order to realize change[3]. The concept of citizen-generated data overlaps with many other terms[4] including 'citizen science'[5], which is a broader approach for involving citizens in scientific research, and 'community-based monitoring'[6], in which community members take part in environmental, natural resource and societal monitoring, similar to the idea of citizen-generated data. Here we will demonstrate the value of using data from volunteers for the SDGs, providing concrete examples of how such data are currently being adopted in support of existing SDG indicators and their potential for contributing to other indicators in the future.

Traditional sources of data collected by national statistical offices (NSOs) (e.g., censuses, surveys, other administrative data, and in situ monitoring) currently provide the main input to SDG reporting[7]. Although valuable and necessary, they, nevertheless, fall short in a number of ways. First, these traditional SDG data sources are costly to obtain, with population censuses ranging from hundreds of millions to 12 billion USD[8] while sample-based methods such as household surveys cost on average between 460 to 1.7 million USD depending on the type of survey[7]. Adding additional pressure to these costs, the Organization for Economic Cooperation and Development (OECD) has recently reported an alarming decline in the financing of sustainable development more generally, particularly in developing countries[9], which will have an impact on SDG reporting. Due to these high costs, the cycle of data collection is often infrequent, and hence these traditional data sources can become quickly outdated. In addition, granular spatial resolution within countries is lacking because the data are reported at the national level so variations within a country are not often captured. This is important from an environmental perspective to understand the linkages between populations and natural resources that are not bound by national borders. Finally, questions have been raised about the openness, availability and accuracy of some official data sets[10]. Using data from the global Open Data Inventory, we illustrate the lack of data availability and openness for SDG reporting in Figure 1a-f. Availability is defined as having social, economic and environmental statistics available for a minimum number of years while openness is a combined factor based on whether the data can be downloaded, are available in non-proprietary formats, metadata availability, etc. (see SI for more details). African countries occupy the lowest rates of availability and openness (Figure 1b) while countries in Asia (Figure 1e) and in Central and South America (Figure 1f) also exhibit data gaps. Even highly developed countries only score between 50 and 85% for these two factors, indicating the need for improvement.

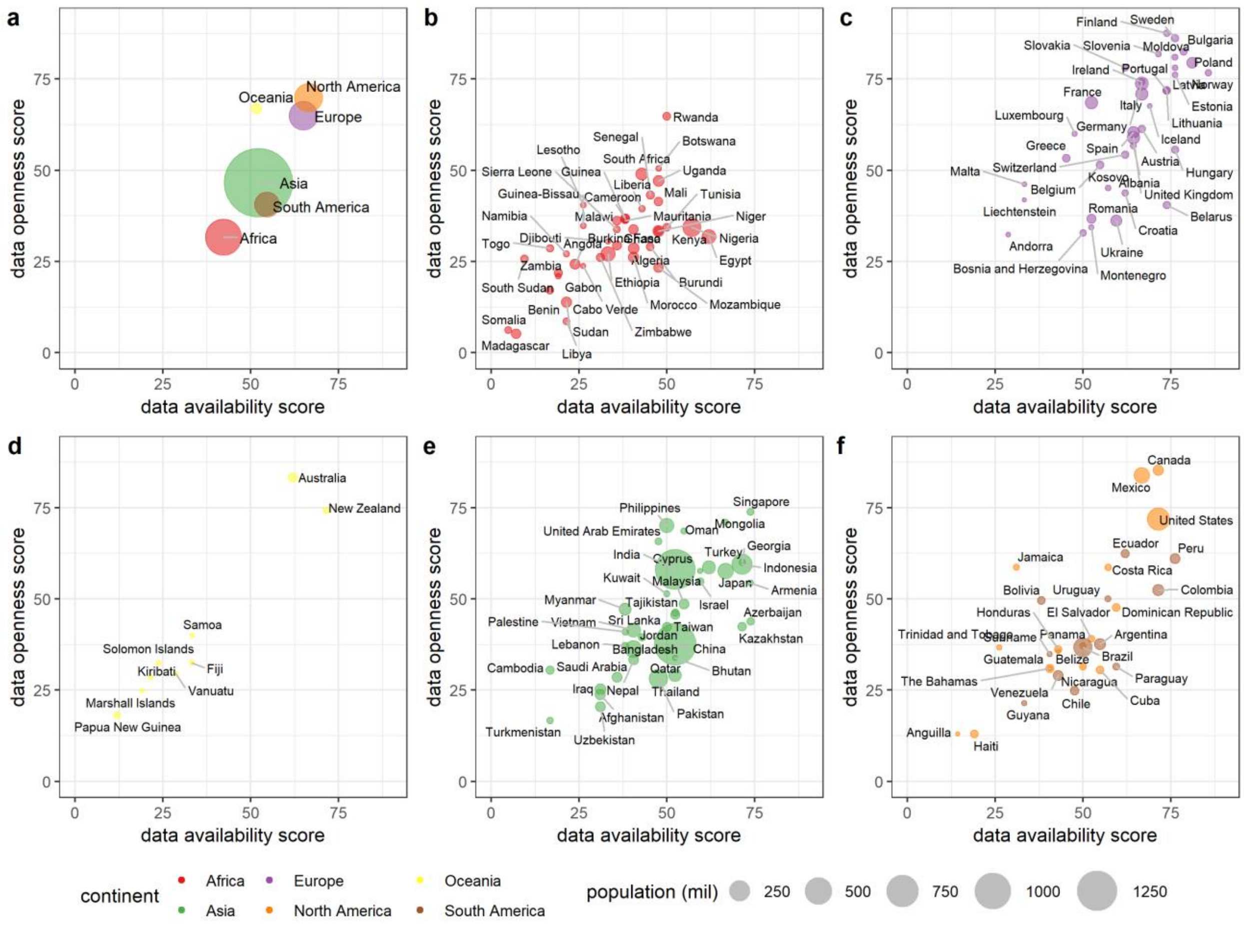

Figure 1: Data availability and openness by (a) continent and country for (b) Africa, (c) Europe, (d) Oceania, (e) Asia and the Middle East and (f) North and South America. The scores are calculated over a 10-year period and weighted by population. Source: Open Data Watch. See Supplementary Materials for details of the scores and methodology.

These gaps illustrate that opportunities for complementing official systems for SDG reporting with non-traditional data sources clearly exist, i.e., contributions can be made to Tier I and II indicators and alternative methodologies and data sources can benefit Tier III indicators (see Box 1). In this paper we aim to demonstrate this potential, by giving examples of where citizen science and community-based monitoring are already contributing to the SDGs and where they might do so in the future. First, we start by placing citizen science and community-based monitoring in the broader context of non-traditional data streams available for SDG reporting. We then present the characteristics of these volunteer data sources, highlighting how the different dimensions of the data can provide value for the SDGs, complementing data already used in SDG reporting. Finally, after presenting the aforementioned examples, we provide a roadmap with concrete actions for how we can mainstream the use of data from volunteers into official SDG reporting at the global, regional and national levels.

Box 1: SDG Indicator Classification by Tiers, Methodology and Current Status

Tier I: *Indicator is conceptually clear, has an internationally established methodology and standards are available. Data are regularly produced by countries for at least 50 percent of countries and of the population in every region where the indicator is relevant.*

Tier II: *Indicator is conceptually clear, has an internationally established methodology and standards are available, but data are not regularly produced by countries.*

Tier III: *No internationally established methodology or standards are yet available for the indicator, but methodology/standards are being (or will be) developed or tested.*

Source: https://unstats.un.org/sdgs/iaeg-sdgs/tier-classification/

All Tier III indicators require a work plan and methodological development to be approved by the Inter-agency and Expert Group on SDG Indicators (IAEG-SDGs). Created by the United Nations (UN) Statistical Commission, this group is comprised of member states of the UN. The proposed methodology is then tested in one or several countries as pilots. After the methodology is refined and finalized, it can be submitted to IAEG-SDG for review and validation.

Tier I data are available for at least 50% of countries whereas Tier II data are not regularly produced. In contrast, Tier III indicators have no standardized international methodology for data collection and are either being developed or will be developed in the future. At present there are 101 Tier I, 84 Tier II, 41 Tier III indicators and 6 with multiple tiers[11]. Countries can also propose alternative indicators based on their available data sets and specific country needs[12]. Moreover, the proportion of the Tier III indicators is much higher for the environment-related SDG indicators, with roughly 30% in the Tier III category.

The ecosystem of data streams available for SDG reporting

To provide context, here we define the larger ecosystem of data streams that are currently being used or could be used for SDG reporting (Figure 2); citizen science and community-based monitoring fall within a subset of this much larger ecosystem. Although traditional data sources employed by NSOs represent the main contribution, a rich collection of other non-traditional data exist. Some of these are starting to be incorporated into SDG reporting but most have yet to be fully exploited[13]. These non-traditional data streams are part of the 'data revolution', which are being recognized increasingly as important, new and innovative sources of information for sustainable development (e.g., by the UN Secretary General's Independent Expert Advisory Group on the Data Revolution)[14]. Examples include:

- Official data sets compiled within national Spatial Data Infrastructures (e.g., buildings, road and hydrological networks, etc.) and geographic information systems;
- Official sensor networks for monitoring weather, air pollution, traffic, etc. [15]
- Commercial data sets that are relevant to SDG reporting (e.g., utility and telecommunication companies, Coca Cola's global monitoring of water quality[10] and commercial 'data philanthropy' spearheaded by UN Global Pulse[16]);
- Earth Observation (e.g., satellite imagery, LiDAR, drones); and
- Multiple sources of data generated by citizens and volunteers, both actively contributed through approaches such as citizen science and community-based monitoring, or passively through, for instance, social media, location-aware mobile phone data, and financial data.

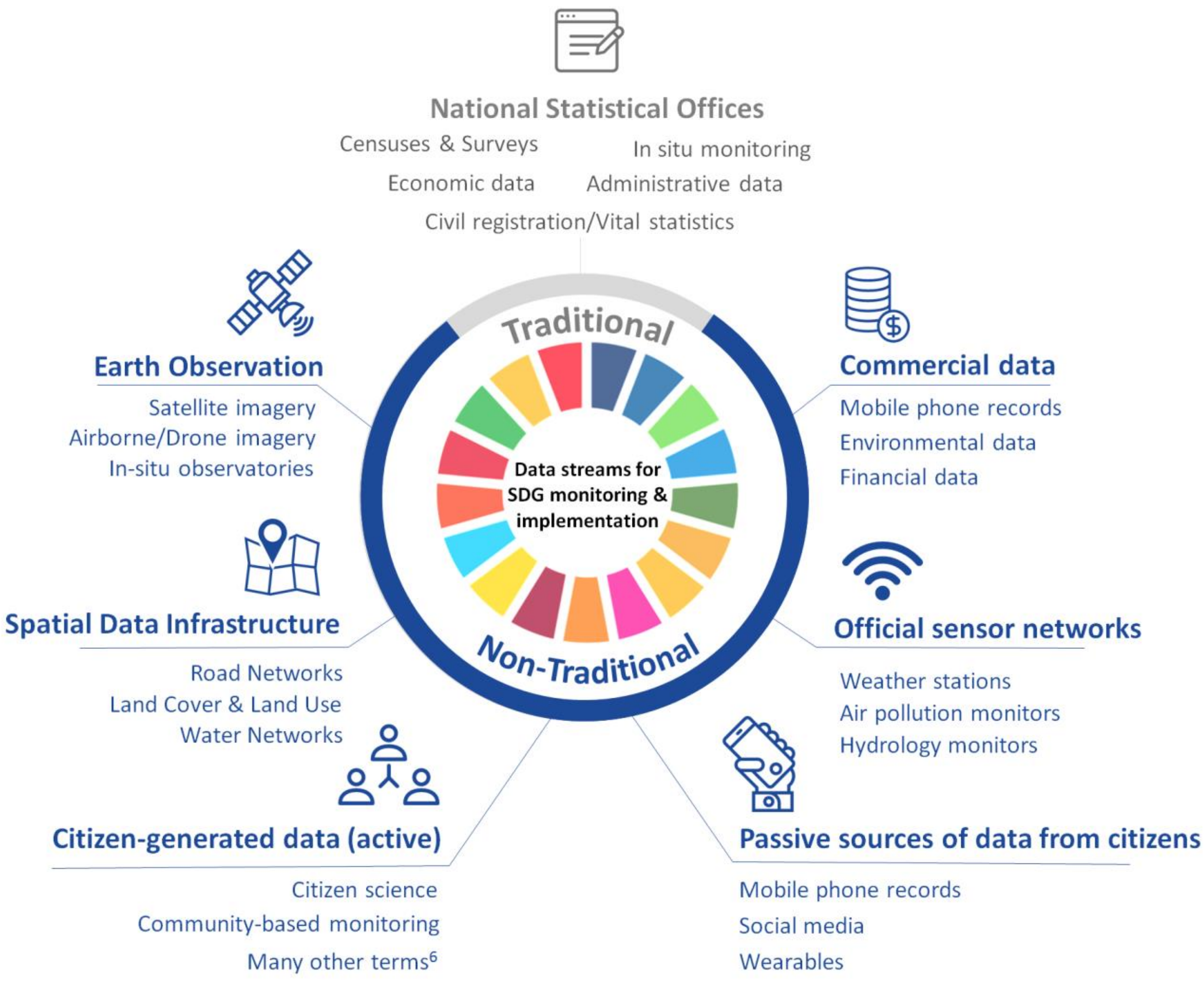

Figure 2: Examples of different data types within the ecosystem of data streams for SDG monitoring and implementation. Source: the authors.

Although our primary focus here is on citizen science and community-based monitoring for the SDGs, data from members of the public can also benefit other non-traditional data streams; for instance, they can fill the in situ data gap needed for creating better outputs from satellite remote sensing (e.g., maps of deforestation) while providing the much needed ground truth data for calibrating and validating these layers. Moreover, volunteers can provide more frequent updates to information contained within a Spatial Data Infrastructure or complement official sensor networks. Initiatives already exist through applications such as Geo-Wiki[17], Collect Earth[18] and OpenStreetMap[19] while national mapping agencies are working actively with volunteers to update components of their Spatial Data Infrastructures (e.g., the Dutch Kadaster[20] and the US Geological Survey's National Map Corps). Amateur weather stations and data from mobile phones are now providing inputs to weather forecasts[21]. More examples are available from a recently published inventory of citizen science activities that address environmental policies[22]. In the next section, we specifically consider data generated from citizen science and community-based monitoring efforts and their value to the SDGs.

The value of data generated by volunteers for the SDGs

To better understand how data generated from volunteers differ from traditional data, we have characterized them according to five main dimensions (Supplementary Table 1). We then discuss how each dimension adds distinct value in monitoring progress towards achieving the SDGs (as summarized in Figure 3).

<u>Spatial dimension:</u> Data from volunteers are often recorded with a geographical location (e.g., photographs geo-tagged with geographic coordinates or location information collected as part of the data collection protocol). Thus, data from volunteers can contribute to the development of spatially explicit indicators, complementing national indicator estimates. In addition, citizen science projects and community-based monitoring initiatives may take place in locations that are otherwise hard to reach or more remote (e.g., through the Adventure Scientists initiative), or they may comprise denser and more abundant observations than traditional data sources, leading to greater spatial representation of the data collected for a particular SDG indicator. Since SDG reporting is done at the national level, individual projects spread geographically should be linked to provide an integrated source of information for monitoring SDG targets. An example is the global platform eBird, which has become integrated with existing regional platforms, harmonizing data with existing projects and increasing the size and reach of the data available[23].

<u>Temporal dimension</u>: The temporal dimension refers to the time period over which the data are collected and the frequency. Some citizen science and community-based monitoring time frames are well suited to monitoring SDG targets, e.g., regular campaigns and continuous data collection. More frequent update cycles as well as better early warning are possible with data collected by volunteers compared to many traditional data sources, which could lead to more up-to-date insights on the progress towards specific SDG targets.

<u>Thematic dimension</u>: Citizen science projects and community-based monitoring cover a wide range of subject areas that are relevant to the SDGs (e.g., water and air quality, marine litter, biodiversity, etc.). Hence this may help to address gaps in Tier III indicators or provide new opportunities for Tiers I and II across a range of SDGs. Data from volunteers can conform to standard thematic definitions or

vocabularies (e.g., in citizen science projects, terminology often is well-defined and adheres to scientific standards). Alternatively, richer, user-defined taxonomies may be used compared to those found in more official data sets. The challenge is to harmonize thematic definitions so that they are compliant with SDG indicator definitions. For instance, a consortium focused on the detection and spread of mosquito-borne diseases is working to create a streamlined suite of methods that allows communities threatened by disease-bearing mosquitos to adopt methods that are most relevant based on regional needs, resource availability, and expertise[24]. Hence, the data collection by volunteers can be designed in a flexible way to ensure comparable thematic definitions that map appropriately to SDG indicators.

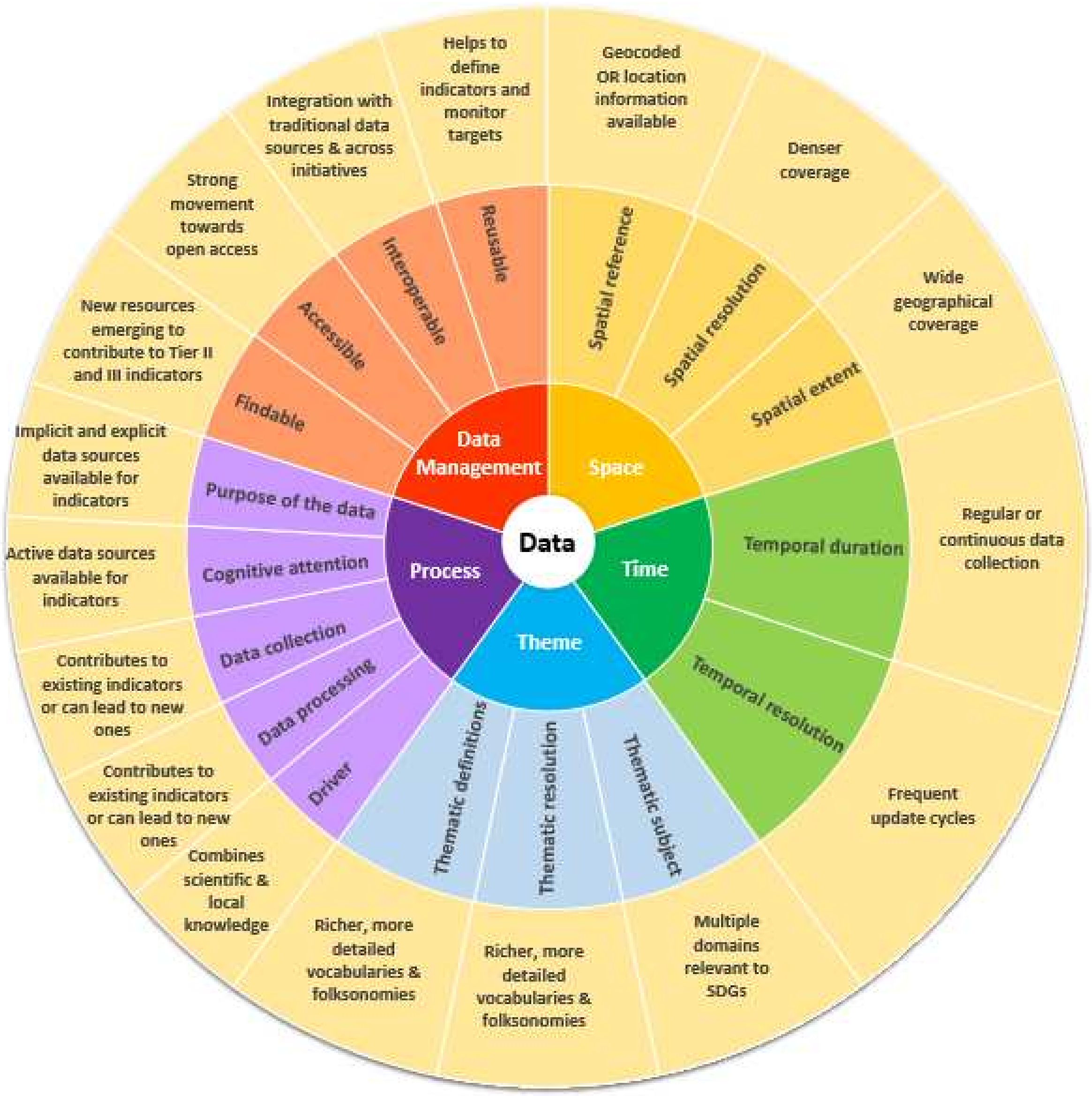

Figure 3: The dimensions and value of data from citizen science and community-based monitoring for the SDGs. Source: the authors.

Process dimension: The purpose of most citizen science projects and community-based monitoring initiatives is not explicitly SDG-related. Yet they may still constitute an important source of data for specific SDG indicators. Data collected following strict protocols can constitute robust data contributions to already defined indicators while freer or more innovative data collection methodologies might provide an additional source of data or become the inspiration for new Tier III methodologies or alternative indicators at the national level. Collegial and bottom up processes, in particular, provide opportunities for tapping into local knowledge while monitoring those SDG targets closely aligned to their priorities and expertise, using predefined and/or alternative indicators.

Data management dimension: The way in which data from volunteers are managed (i.e., whether they are in line with the FAIR principles (findable, accessible, interoperable, reusable))[25] will influence the extent to which they can provide value for SDG monitoring. The accessibility of volunteer data is a prerequisite to the use (or reuse) of the data as part of an already defined indicator (especially Tiers II and III) or as input to an alternative indicator. As more data sets from citizen science and community-based monitoring are registered in portals (e.g., the GEO Data Access Broker), it will become easier to identify data sources that can contribute to Tier II and III indicators or alternative indicators at the national level.

In summary, data from citizen science and community-based monitoring can complement traditional data sources, fill in data gaps using established Tier I and II methodologies or contribute to Tier III indicators where traditional data sources are not currently available and/or methodologies are currently lacking. In the next section, we present examples of where citizen science and community-based monitoring are already contributing to Tier I and Tier II indicators.

Filling data gaps in Tier I and Tier II indicators

Tier 1 indicator 15.5.1 "Red List Index" is an example of where citizen science is already making real contributions to the SDGs at a global level. Compiled by the International Union for Conservation of Nature and Natural Resources (IUCN), the Red List Index (also known as the IUCN Red List of Threatened Species) provides indicators that capture risk of extinction over time for four taxonomic groups: birds, mammals, amphibians, and corals. The organization BirdLife International compiles all the data on birds for the Red List[26], which comes from their network of scientists and more than 5,000 trained volunteers[27]. In addition, BirdLife International uses data from other relevant citizen science projects such as eBird for their list of threatened bird species and hence indicator 15.5.1; see, for example, the use of Birdata and eBird from Australia[28]. In the case of mammals, citizen scientists are helping identify species from photographs taken by camera traps including the crowdsourcing of threatened species[29].

Another example is the contribution of citizen science to the establishment of protected areas. More than half of the world's Key Biodiversity Areas (KBAs), which are areas designated as having international importance for biodiversity, overlap with existing protected areas[30]. KBAs contain more than 13,000 Important Bird and Biodiversity Areas (IBAs), which are established by BirdLife International using data from their volunteer network[31]. Hence citizen science contributes to additional Tier I indicators such as 6.6.1 "Change in the extent of water-related ecosystems over time", 4.5.1 "Coverage of protected areas in relation to marine areas", 15.1.2 "Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type", and 15.4.1 "Coverage by protected areas of important sites for mountain biodiversity".

At a more local level, we present two country case studies where community-based monitoring is providing supplementary data. In the Philippines, community-based monitoring has enabled local government units and community volunteers to collect household census data on factors such as poverty, nutrition, health, education, housing, and disaster risk reduction[32]. These data are used by the Philippine Statistics Authority to enhance local-level statistics on 32 SDG indicators, including both Tier I and II[33]. Moreover, data from volunteers have been formally recognized in the Philippine Statistical Development Plan as a means for enhancing local data collection for the Philippine Statistical System[34]. More recently, an Accelerated Poverty Profiling mobile platform has been introduced along with a suite of tools to enhance data collection, analysis and storage, thereby streamlining data-to-action linkages by local government units[32].

In Peru, citizen participation in water quality and quantity monitoring has increased in the past decade as a means to fill long-term data gaps, improve water resource management and address water use conflicts[35]. The National Water Authority of Peru, which aggregates and reports national data related to SDG 6 (clean water and sanitation), has supported participatory water monitoring programs to enable community involvement in data collection for watershed planning[36]. Meanwhile, complementary community-based monitoring initiatives have emerged at regional scales. In the Andean region of Peru, local stakeholders, academic institutions and NGOs formed the Regional Initiative for Hydrological Monitoring of Andean Ecosystems (iMHEA) to improve management of local water resources. The iMHEA network co-developed a robust and standardized water monitoring protocol, and leverages partnerships with local universities to provide resources for training, equipment calibration, data analysis and data management[37]. Such initiatives could produce credible, supplemental data for the Tier II indicator 6.3.2 "Proportion of monitored bodies of water with good ambient water quality" while also directly supporting the achievement of SDG 6.b "Participation of local communities in improving water and sanitation management". Such synergies demonstrate the optimal use of community-based monitoring, where the data contribute to measuring SDG indicators as well as directly achieving the SDG targets. Yet we need more solid guidance on how to scale up these experiences to other locations.

In addition to Tiers I and II, citizen science and community-based monitoring have the potential to contribute to Tier III indicators, both in terms of filling data gaps and in methodological developments.

Filling data gaps in Tier III indicators

Here we provide examples in three areas: monitoring food waste; climate change; and marine pollution. Food waste is a global issue with enormous health, economic and environmental impacts. Although tools exist to support businesses, governments and agricultural producers, citizen science approaches could be used to monitor the amount of food wasted over time, contributing to SDG target 12.3. For some European countries, robust data using standardized methods already exist[38]; these methods could be replicated in countries with data gaps while involving communities in refining these methods (e.g., determining what waste streams should be measured based on the cultural context and how best to quantify them). Technological solutions could help monitor elements of food waste such as food expiry dates and the use of 'smart' garbage bins.

Secondly, citizen science could support monitoring of progress towards SDG13 through increasing human and institutional capacity to act on climate change (SDG indicator 13.3.2). An example is the climate-smart agriculture MAIS program in Brazil[39]. Small scale farmers who do not have access to expensive soil and crop monitoring services are provided with the technology and knowledge to monitor soil moisture and implement adaptive soil and land management. The proxy indicators derived from these activities include the number of farmers and growers using advice to produce locally appropriate diverse and sustainable crops despite changing conditions. In sub-Saharan Africa, farmers were equipped with low cost rain-gauges; based on the high-density data set obtained, national meteorological services were able to provide the same farmers with agrometeorological advice on the evolution of the rainy season and the most suitable farming practices.

Third, essential to SDG14 is the target of achieving substantial reductions in marine pollution, including nutrient pollution and marine debris in coastal waters (SDG indicator 14.1.1). Eutrophication is increasing in coastal waters, and UNEP, the custodian agency responsible for methodological development and global reporting for this indicator, recommends the combined use of remote sensing and citizen science for large-scale monitoring with validation by citizens[40,41]. Mobile applications such as eyeonwater.org, citclops and Earthwatch's Freshwater Watch enable volunteers to contribute data on the color of coastal waters, which serves as a simple and accessible baseline indicator for eutrophic trends that can be used in tandem with remote sensing data[40,42]. The National Aeronautical Space Agency (NASA) in the US is exploring citizen science potential within general aviation to contribute aerial photos to assess eutrophication[43].

As with eutrophication, citizen science communities are already engaged with quantifying marine debris in ways that could contribute to SDG 14. At present, quantification of floating marine debris, specified in indicator 14.1.1, relies mainly on visual observations by scientists, with no standardization in approaches or an internationally agreed protocol[41]. Beyond quantifying debris that is floating, members of the public often participate in marine debris clean-ups[42,43], often recording marine debris found with the Tangaroa Blue Foundation (i.e. part of the Australian Marine Debris Initiative), OpenLitterMap, Marine Debris Tracker, and other programs. Synergies between marine and river pollution monitoring by citizen scientists could also be investigated for SDG reporting[44]. New technologies such as computer vision are being employed in combination with visual interpretation of drone imagery by citizen scientists in quantifying marine debris (e.g., in the Plastic Tide project). This could be extended to visual interpretation of imagery from larger scale aerial surveys, where volunteers could work together with NGOs and government agencies in quantifying marine debris.

In addition to supporting the existing system of SDGs, citizen science and community-based monitoring provide opportunities to contribute to the generation of additional goals and targets where gaps can be identified. Air quality monitoring is a good example that demonstrates this potential as outlined below.

G***enerating additional goals and targets: an air pollution example***

Currently, two SDG indicators are linked to air quality: (1) 3.9.1 Mortality rate attributed to household and ambient air pollution, and (2) 11.6.2 Annual mean levels of fine particulate matter in cities[45]. These indicators, however, provide neither the actionable information that cities and communities need to manage their local conditions, nor do they contribute to an increased understanding of the health impacts of air pollution.

Citizen science and community-based monitoring can fill this gap through the novel application of traditional sensors such as Palmes' Diffusion Tubes[46] and the ongoing efforts to develop reliable low-cost electrochemical sensors[47]. These advances are attracting investment; for instance, Plume Labs (France) is developing personal-scale individual sensors ("The Flow") to track indoor and outdoor air pollution for PM2.5, NOx, Ozone and Volatile Organic Compounds (VOCs) as well as algorithms to predict air pollution using 12,000 environmental monitoring stations across 60 countries. CurieuzeNeuzen (Curious Noses) is a citizen science project on monitoring air quality in Antwerp, Belgium, that involved 2000 participants. The project resulted in both positive behavioral change in the participants while simultaneously driving political debate on air pollution and mobility measures[48]. Due to its success, Curious Noses has now been upscaled to the broader Flanders region of Belgium with the involvement of 20,000 participants[49]. Propeller Health is another innovative example that integrates data from sensors on Asthma inhalers with pollution information.

The current level of investment and research indicates that some air quality indicators, such as CO_2, NO_2 or Particulate Matter, may see increased adoption and use of low-cost sensors in the coming decade, especially within action-oriented monitoring schemes that can tolerate indicative levels rather than high-level accuracy for compliance purposes. Importantly, environmental protection agencies are showing commitment to the use of low-cost sensors and citizen science in air quality management at the national (e.g., the US, Netherlands and Ireland), regional (e.g., the EU), and UN level. Therefore, the opportunity exists to build a global network of projects that could be linked to a potentially new indicator that will be in place for future global environmental monitoring efforts.

We have demonstrated the value of citizen science and community-based monitoring for the SDGs based on just a few of many examples that exist, yet when and how such data are being used for the SDGs, even if indirectly or informally, is not always clearly highlighted by the users of the data. Hence, we need to move forward, and work towards mainstreaming citizen science and community-based monitoring as accepted methodologies for SDG monitoring and reporting. Below is our suggested roadmap for building support and creating operational workflows within the UN and its member countries.

A roadmap for integrating citizen science and community-based monitoring into the SDGs

A first step on this path is for organizations such as the Citizen Science Global Partnership (CSGP), citizen science associations and their member organizations from around the world to become an active part of the current SDG reporting system at global, regional and national levels, as elaborated below.

The SDG goals, targets and indicators have been developed by the IAEG-SDGs (Box 1), in consultation with experts from the UN, civil society, businesses, academia and NSOs. This development process is still ongoing, whereby Tier III indicators are moved to Tier II and eventually Tier I, with annual reporting to the High Level Political Forum for Sustainable Development. Each indicator is the responsibility of a custodian agency, which works with experts to develop indicator methodologies. Pilot projects are then run in designated countries to demonstrate the methodology and the data collection process.

To be part of this global reporting process, there are two key actions needed. The first is to find custodian agencies that are willing to champion citizen science and community-based monitoring within their own organizations. The second is to identify the indicators to which citizen science and community-based monitoring could contribute. Here we take the example of floating marine debris. As outlined above, we have already identified many initiatives that are involved in marine debris identification and clean up, providing both temporal and spatial scalability, a high level of citizen participation and project longevity. Representatives from these initiatives need to be brought together with the UN custodian agency, in this case UNEP, and experts in marine debris science, to agree a consistent set of protocols for measuring and collecting the data for SDG reporting. Clear guidance and usable tools need to be offered to citizen science and community-based monitoring initiatives to make the data that they create available and fit-for-use within the SDG framework. Countries with strong national citizen science and community-based monitoring projects could then act as pilots for this indicator (e.g., Australia, Chile, Ireland and the UK). In this way, data from citizen science and community-based monitoring could be formally brought into the SDG reporting process at the global level.

In parallel, we also need to work at the national level, particularly as responsibility for the SDG reporting process lies with national governments[50]. The CSGP, citizen science associations and their members should, therefore, work actively with the UN Statistical Commission to identify the best institutional frameworks, and to offer guidance that will encourage NSOs to bring citizen science and community-based monitoring into the scope of official statistics. This could include creating opportunities for peer-to-peer networking among statisticians to share lessons learned and best practices for using citizen science for SDG monitoring and harmonizing data from citizen science and community-based monitoring with more traditional sources of data, including an agreed set of accepted protocols and minimum data quality standards required from citizen science and community-based monitoring projects. Citizen science communities of practice need to be developed within these organizations and across the UN, as well as active involvement within current communities of practice (e.g., the Group on Earth Observations and the WeObserve project[51]), to encourage knowledge exchange and facilitate the creation of durable workflows that integrate data from citizen science and non-traditional data more generally. Aligning citizen science and community-based monitoring initiatives with the priorities of decision makers at the UN and in NSOs will increase the likelihood of its adoption in SDG monitoring and reporting. Similarly, we should seek to replicate models of good practice already taking place nationally. As an example, Australia has developed its own "Method for Australia's SDG baseline assessment" by choosing priority targets and indicators that allow the country to report and monitor quantities adapted to their country's specificity[52]. For many of these "proxy" indicators, citizen participation provides the main data collection mechanism.

Elsewhere governments are developing institutional frameworks to encourage public bodies to work with citizen scientists (e.g., the US White House Memorandum on Citizen Science; the US Crowdsourcing and

Citizen Science Act, which was incorporated into Section 402 of the American Innovation and Competitiveness Act; the European Open Science Policy Agenda; the recommendations of the European Open Science Policy Platform (OSPP); and action 8 of the EU roadmap to streamline environmental monitoring, which calls for the wider use of data from citizen science[53]). Hence, the citizen science community should work with decision makers to craft policies that authorize, encourage, and provide guidelines for the appropriate use of citizen science for SDG monitoring in other countries around the world.

Another key feature of the road map will be a set of concrete actions for addressing the quality of citizen science data, which will be the number one concern for NSOs. Therefore, the citizen science community should work with statistical agencies and the relevant academic scientific community to develop robust methodologies for data quality assurance, assessing the representativeness, uncertainty statistical accuracy, and potential bias in the data. The quality of data from citizen science and community-based monitoring can be evaluated using the same measures as any other official data (e.g., ISO19157, which is a standard used to evaluate the quality of spatial data). This includes measures such as positional and thematic accuracy, temporal currency of the data, completeness and representativeness over space and time and whether the data are fit-for-purpose for the application to which they are intended. At the same time, the data may need additional types of quality assurance specific to the nature of citizen science data but many new, robust methods are now available[54]. As with any scientific endeavor, quality assurance will be needed at all phases, from project design and implementation to validation of project results. The Mosquito Alert citizen science initiative, for example, has shown that data collection is cheaper and quicker but with the same level of accuracy as traditional methods[55]. Today there is a greater awareness of the factors that influence data quality in citizen science projects, including the design of training, protocols, and technology[56], data review and vetting processes[23], and community communication and collaboration[57]. This best practice needs to be shared with the UN, custodian agencies and NSOs. They need to be paralleled by efforts to raise awareness of these data quality assurance mechanisms so that perceptions (and not just procedures) change that may otherwise still stand in the way of the using data from citizen science and community-based monitoring for the SDGs.

In addition to data quality, interoperability is paramount to interpreting and sharing the data consistently and integrating the data across different citizen science and community-based projects, and with traditional and non-traditional data sources (e.g., satellite imagery). For example, citizen science researchers and practitioners affiliated with the United States, European, and Australia citizen science associations, in collaboration with SciStater.com and other partner organizations, have been developing a new data and metadata standard for Public Participation in Scientific Research (PPSR), which is adapted from the Darwin Core standard for biodiversity[58]. Aligning PPSR core standards with the SDG indicators and tiers can reveal where citizen science and community-based monitoring have the potential to contribute the most, maximizing the efficiency of data infrastructure, storage and curation. Future iterations of the PPSR core standard can incorporate economic, environmental and societal dimensions of the SDGs. Cloud computing, Artificial Intelligence and other frontier technologies are also making this integration possible.

Finally, we need to create a trusted environment where statistical agencies and citizens can contribute, find, and re-use each other's data, adhering to the FAIR data principles, while at the same time understanding the potential privacy risks and adhering to applicable data privacy laws. The US White House Office of Science and Technology Policy memorandum on citizen science, issued on September 30, 2015, provides guiding principles, including providing volunteers with appropriate access to their data, ensuring meaningful engagement of the public in scientific research, and giving appropriate attribution for volunteer contributions. In addition, the European Citizen Science Association has developed a set of 10 principles for citizen science that should be followed[59]. Civil society has a key role to play in developing this trusted environment further, creating a space in which their observations have the power to hold governments accountable, raise awareness of the importance of the SDGs to civil society more broadly, and potentially lead to collective transformation that reduces poverty, improves equality and halts environmental degradation.

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